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Analysis of the Articulated Total Body (ATB) and Mathematical Dynamics Model (MADYMO) Software Suites for Modeling Anthropomorphic Test Devices (ATDs) in Blast Environments

by Neeraj Shukla

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14. ABSTRACT

The U.S. Army Research Laboratory's Survivability/Lethality Analysis Directorate (ARL/SLAD) is developing a modeling proficiency for ground vehicle systems exposed to under-body blast (UBB) threats with predictive crew casualty analysis capabilities to support live-fire test and evaluation (LFT&E). This report details a comprehensive comparison of two software suites used for modeling anthropomorphic test devices (ATDs) in blast environments conducted to down-select to one for future modeling efforts. After extensive use of both software suites to model laboratory and live-fire experiments with ATDs, it is clear that the mathematical dynamics model (MADYMO) software suite offers many advantages over articulated total body (ATB). These advantages include reduced model setup time and pre-processing, increased amount of model features, increased level of temporal and special resolution, a larger user community, and thorough commercial software support. From these results, the logical path forward for the under-body blast methodology (UBM) program is to use the MADYMO software suite for modeling ATD response to blast loading.

15. SUBJECT TERMS

ATB, ATD, FEM, Hybrid III, MADYMO, rigid-body, underbody, blast IED

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1. Introduction and Objectives

Many automobile manufacturers use rigid-body and finite-element (FE) models to simulate anthropomorphic test device (ATD) responses in car accidents. Today, the Army is using these models to simulate ATD response in blast environments to support live-fire test and evaluation (LFT&E) of ground vehicle systems. Two software suites are compared in this report: the articulated total body (ATB) model and the mathematical dynamics model (MADYMO).

The objective of this report is to illustrate the advantages and disadvantages of using one software suite over the other for modeling ATDs in blast environments. The analysis and evaluation presented here support the conclusion that MADYMO is the superior software suit and should be the choice of modelers for the under-body-blast methodology (UBM) program.

The U.S. Army Research Laboratory's Survivability/Lethality Analysis Directorate (ARL/SLAD) has used both ATB and MADYMO software suites for modeling ATDs in blast environments. Specifically, we modeled laboratory experiments simulating the effects of blast on test mannequins as well as system-level LFT&E of ground vehicle systems with ATDs exposed to under-body blast (UBB) threats. In this report, we describe the methodology used to model these experiments and test events with both ATB and MADYMO. We compare the features and capabilities of each code and provide results detailing the relative performance of each. The categories used for comparison are licensing costs, ease of use and productivity, and correctness of results. Both ATB and MADYMO have shown to be useful models with trend-predicting capabilities. The accuracy of the model results are completely dependent on the skill and expertise of the modeler in addition to the amount of information the modeler has about the test event being modeled, including test data traces, pictures, video, etc. Our justification for preferring MADYMO over ATB for modeling ATD response to UBBs is that MADYMO offers software support and is an extensive software suite with capabilities that enable the user to create and edit models easily. MADYMO provides the facilities to create accurate, fast-running models for UBB applications.

2. Software Introduction

The ATB software was developed for the Air Force Research Laboratory (AFRL), and it originated from the Crash Victim Simulation (CVS) program from Calspan (*1*). ATB therefore accedes to a legacy of modeling and simulation effort. AFRL has used ATB to simulate the kinematics of occupants during aircraft ejection (*2*). Unfortunately, ATB has not been actively developed for some time, and there is no software support available. The pre- and post-processor available to edit and visualize an ATB input file is "ATB3I: The Intuitive Intelligent Interface for

ATB." ATB input files are text files, which are segmented into "CARDS" that describe the different features of the simulation: the occupant, the "vehicle," the outputs, run controls, etc. ATB3I is also the post-processor for ATB and is capable of playing animations of the simulations.

MADYMO is a software suite developed and managed by TNO Automotive Safety Solutions (TASS), which is headquartered in the Netherlands. MADYMO comes with full software support and training by TASS in North America, who continues to produce new updates with enhanced features for ATD and human models. MADYMO is used by most major automobile manufacturers, accident reconstruction organizations, and defense organizations and contractors including the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC), U.S. Navy Naval Air Systems Command (NAVAIR), General Dynamics Land Systems (GDLS), the Norwegian Defense Research Establishment (FFI), the Council for Scientific and Industrial Research (CSIR), and ARL. The pre-processor used to edit and visualize MADYMO input files is called "XMADGIC." The input files are extensible markup language (XML) text files. The MADYMO workspace software suite also includes MADPOST, a post-processor for animations and videos, and Objective Rating, a post-processing tool for comparing signals from physical tests and simulation results.

With both ATB and MADYMO we can model an ATD with a connected sequence of rigid-body elements. Specifically, we used the programs to model the Hybrid-III (H3) ATD. Each rigid-body element is non-deformable and is represented with a mass, center of gravity, and moments of inertia. The surface of each body element can be an ellipsoid, hyper-ellipsoid, or a plane. Figure 1 shows the MADYMO ellipsoid representation of the rigid-body model H3.The rigid-body elements of the H3 are connected using different types of joints such as bracket joints, hinge-joints, and ball-and-socket joints. Each joint can have specified properties such as damping and friction coefficients, which can change the motion of the body elements from applied forces.
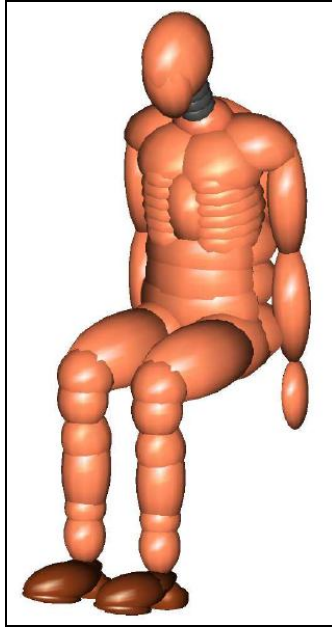
Figure 1. MADYMO H3 50th percentile
ellipsoid base model (*3*).

The software products also can be used to model the blast test environment, which includes the vehicle, seats, and ATD. The vehicle system can be modeled with simple bodies such as ellipsoids and planes in both software suites. MADYMO has the additional capability of modeling the vehicle system with finite elements including shell, solid, and beam elements. We have created all the vehicle models in-house; however, FE models of vehicles created in other programs such as LS-DYNA can be reused in MADYMO. The initial conditions of the test environment are set by the user and the programs then calculate motions and forces using principles of classical mechanics. The results of these calculations are force-time and moment-time data histories that can be compared to experimental data.

3.   General Software Features

ATB and MADYMO both have a rigid-body modeling capability that is quite similar. However, this is where the similarities between ATB and MADYMO end. Also, the future of ATB is very bleak. ATB is far less supported than MADYMO, and no new releases of ATB are expected. Overall, MADYMO has a much larger and well-supported feature set than ATB. Because ATB has a smaller set of capabilities, the ATB solver also has smaller computational requirements than MADYMO. Both MADYMO and ATB are packaged with pre- and post-processor applications that assist in creating models, running simulations, and analyzing results. ATB models are composed of only rigid-body components while MADYMO models can include rigid-body components as well as FE analysis. ATB is capable of limited interaction with other

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models, such as incorporation of deformable segments by using data from an external FE analysis. This feature appears to be poorly supported and was not exercised in this evaluation. MADYMO, on the other hand, is very capable of interacting with other models including complete step-by-step coupling with LS-DYNA for FE analysis, decoupled interaction with an external model via prescribed structural motion of a FE mesh, coupling with MATLAB for complex switching and control logic, as well as the capability of outputting D3PLOT files for use in external applications such as LS-PrePost. MADYMO input and output formats are also supported by third-party pre- and post-processor applications suites such as Altair Hyperworks, while ATB formats are not supported. The amount of ATB users is declining rapidly while MADYMO users include large communities from the commercial and defense sectors.

3.1 Software Suites

The software included with the ATB install is the ATB solver and the ATB3I pre- and post-processor. The ATB solver is a Windows command-line executable and the graphical user interface (GUI) for ATB3I runs using the Microsoft .NET framework. The ATB3I pre- and post-processor is used to create and edit ATB model input files. It is also used to visualize animations created from ATB simulations. It does not have a data trace plotting capability.

The MADYMO software suite includes the MADYMO solver and the MADYMO workspace. The MADYMO workspace is a compilation of several dedicated pre- and post-processing applications for MADYMO models, simulations, and input/output files. The MADYMO workspace includes the following pre-processors: XMADgic, used to create and edit MADYMO models; Coupling Assistant, used to couple the MADYMO model with FE codes such as a coupling a MADYMO H3 model to a LS-DYNA FE code; and Exchange, used to modify certain variables in a MADYMO model for parametric analyses. The workspace also includes the following post-processors: MADPost, used to visualize animations, videos, and plot data traces; Protocol Rating, used to generate consumer safety rating scores for specific safety protocols such as a "four-star safety rating;" and Objective Rating, used to quantify correlation between signal responses from physical tests and simulation results.

The latest release of the ATB solver is version V3.1, which was released in 2003 and the latest release of the ATB3I pre- and post-processor is version 2.0.3, which was released in 2008. AFRL is no longer formally supporting the ATB software, and updates and enhancements from user groups have ceased. In comparison, the latest release of the MADYMO solver and workspace including pre- and post-processors is version 7.3, which was released in 2011.

The difference in feature sets and lack of ATB updates is why there is a large difference in the ATB and MADYMO hardware and software requirements. ATB only requires 8 MB of RAM while MADYMO requires 256 MB of RAM and recommends 512 MB or more. The ATB program is currently only built for the 32-bit Windows operating system (OS). The solver is a command-line-based Windows executable file. The source code of ATB is in the FORTRAN programming language and can be compiled and built for other OSs if necessary. The

MADYMO solver is available for 32- and 64-bit Windows systems with symmetric multiprocessing (SMP). A SMP system is a multiprocessing computer system where the processors use shared memory. The MADYMO solver and workspace are also available on 32- and 64-bit Unix and Linux systems with SMP or massively parallel processing (MPP). A MPP computer system uses distributed memory on many computational nodes that communicate using the message passing interface (MPI).

3.2 Model Components

ATB and MADYMO can both be used to model simple rigid-body systems with ease. However, the MADYMO software has many additional advanced features which can add spatial and temporal resolution to a model. These features provide flexibility to the user to add as much complexity to the model as is needed for a specific use-case. An overview of the feature comparison between ATB and MADYMO is presented in table 1.

Table 1. ATB and MADYMO feature overview.

Feature	ATB	MADYMO
Body types	Rigid only	Rigid bodies, flexible bodies, and flexible beams
Joints	6 types	17 types
Springs and dampers	Kelvin restraints	Kelvin, Maxwell, and Cardan restraints
Surfaces	Planes and ellipsoids	Planes, ellipsoids, hyper-ellipsoids, and FE facets
Contacts	Functions based on deflection and rate of deflection or Functions based on force-deflection, inertial spike, energy absorption, permanent deflection, and friction	Functions based on loading, unloading, hysteresis, and damping
Seat belts	Simple restraints by initial slack, friction, and strain-force and deflection-force functions	Simple restraints or full FE restraints with material models
Airbags	Gas flow model with inflatable ellipsoid	Gas flow model with inflatable FE structure
Gravity	Gravity vector	System acceleration element
Prescribed motion	Acceleration, velocity, or position time history	Acceleration or position time history
Prescribed structural motion (PSM)	None	Nodal time acceleration or position time histories prescribed to an FE mesh
Force and torque loading	Applied forces/torques and joint actuators	Rigid body and joint force and torque actuators
FE coupling	Coupling with externally completed FE analysis for one deformable segment	Step-by-step live coupling with external FE models for full integration
Built in FE modeling	None	Beams, shells, solids, 30+ material models and integration of rigid and FE model components
Control elements	None	Built in sensors, operators, actuators and control elements (such as switches) and/or coupling with MATLAB for more complicated control logic

While ATB only has simple rigid-body modeling, MADYMO has what it calls multi-body (MB) modeling, which includes rigid-body models as well as flexible bodies and beams. These flexible bodies can experience permanent deformations and will displace according to the deformation. This feature is useful for modeling parts of the vehicle or personnel protective equipment (PPE), such as a helmet, which permanently deform and impart loading to a test mannequin. The ATB code has the capability of implementing deformable bodies by using external FE analysis tools. The user must develop the FE model separately and perform a modal analysis to include the deformable body in ATB (*4*). Rigid-bodies in both codes are strictly non-deformable and maintain constant moments of inertia.

Bodies are connected using many types of joints that are defined in both software products. Although the naming convention of joints differs, each necessary kinematic joint is possible in both codes. One example of the same joint with different names is the hinge joint: The hinge joint, which has one angular degree of freedom, is called a pin joint in ATB and a revolute joint in MADYMO. Both of these joints function identically. MADYMO also has an added set of joints that make it easy to create joints using different coordinate systems such as having three types of spherical joints: spherical joint with Euler parameters, spherical joint with Euler angles, and a spherical joint with Bryant angles. ATB and MADYMO use joint restraints to constrain the possible motion of the rigid bodies connected by a joint. Although implemented in slightly different ways, joint restraints including elastic loading, damping, and friction coefficients can be used in both models to restrict kinematics. MADYMO can also have active loading applied to joints. In addition to using joints as connections, rigid bodies can also be connected with spring-damper systems. In ATB, spring-damper forces are defined by setting coefficients for the spring force and the viscous force. This represents a Kelvin restraint—a spring in parallel with a damper. In MADYMO, there are more options for restraint systems including the following: Kelvin, Maxwell, and Cardan restraints. Maxwell restraints are forces calculated from a system with a spring in series with a damper. Cardan restraints apply opposite torques on the connecting bodies that vary with the angle at which they are oriented. MADYMO also offers additional features for implementing these types of restraints including hysteresis, damping, initial strains or deflections, and dynamic amplification. This added flexibility in MADYMO allows for the creation of models with more degrees of freedom.

Each of the bodies modeled in ATB and MADYMO can have the surfaces modeled by a set of ellipsoids, hyper-ellipsoids, and/or planes. In addition, MADYMO is capable of using FE facets as the surfaces of a rigid body. Multiple surfaces can be connected to one body. For example, a foot may be modeled as one body with a single mass, with five different ellipsoids to form the shape of a foot. The surfaces are used for the contacts between bodies as well as for visualization purposes in animations.

Contacts are one of the most important definitions for rigid-body models, especially models for UBB applications. The contacts are critical in the loading from the floor and seat of the vehicle to the feet and pelvis of the occupant. The contacts in both models must be explicitly defined or

the surfaces will simply pass through each other. In both ATB and MADYMO, the contacts are defined for plane/ellipsoid and ellipsoid/ellipsoid interactions. MADYMO refers to this group as MB-MB contacts. In ATB, there are two ways of defining the contacts. The first way involves defining multiple rate-independent functions that contribute to the total force including the base loading function, inertial spike function, energy absorption function, permanent deflection function, and friction function. The second method is by defining four functions of deflection and rate of deflection to combine into one rate-dependent contact function. If x is the deflection of two bodies and x' is the rate of deflection, then the second method force function is

$$f(x) = f_1(x) + f_2(x)f_3(x') + f_4(x')$$

(1)

The functions $f_1, f_2, f_3,$ and f_4 do not have any physical meaning, but they are rather a mathematical construct to sum into the total contact force. ATB contacts also use a friction function in the definition. MADYMO incorporates many more contact models than ATB due to the need to define FE-MB contacts and FE-FE contacts. The contact definitions in MADYMO include functions to represent loading, unloading, hysteresis, damping, and friction. Although there are differences in the implementation of these contacts, the basic concepts remain the same for MB-MB contacts in MADYMO as with the contacts in ATB. In both models, the user is typically not expected to generate contact functions for the ATD from scratch; rather, default contact functions are provided that the user may "tweak" to achieve the most reasonable results. For some equipment, such as a seat cushion, it may be incumbent on the user to define a contact function. In our experience, the default contact functions provided with MADYMO appear to be more robust and accurate than those provided with ATB.

In ATB, the seat belts are modeled using the "harness belt" system. The "harness belt" contacts the H3 model in about 10 points and can slip around to contact different segments. The dynamic properties of the harness belt are defined by the initial slack, friction, strain-force functions, and force-deflection functions. The seat belts were modeled in MADYMO using full FE belts with up to hundreds of contact nodes between the belt and the H3. MADYMO defines the dynamic properties of the belt with friction, strain, elongation, and damping functions. MADYMO also has the capability of modeling simple belts similar to harness system in ATB. One difference is that the simple belt in MADYMO does not allow slippage of the contact points between the belt and the occupant while the ATB harness system does allow slippage; however, if slippage is desired, then the user is compelled to use the FE belt capability. Accurate modeling of belt systems is important for modeling UBB effects. For example, the restraint system strongly influences spine compression and moments when the primary loading axis is vertical.

After defining surfaces, contacts, and belts, the next components to add to the model are the loading conditions, which will simulate real-life tests and experiments. One way of applying loading in ATB and MADYMO is using an accelerative field. This feature is very similar in both software suites. An acceleration function is defined and applied to certain bodies or systems. The acceleration can be used to load an occupant from the seat into the dashboard of a vehicle,

representing the opposite of the acceleration of a vehicle hitting a barrier and coming to a stop very quickly. Accelerative fields are also used to apply gravity to models. When applied to UBBs, accelerative fields can be used to load the occupant downwards into the floor and seat to model drop tower tests.

In ATB, only a constant velocity field can be applied using the "Gravity Vector" in the run-time control parameter definition. In MADYMO, one may define acceleration functions as a list of *xy* coordinate pairs representing the acceleration over time. The function is interpolated between the supplied points by using linear or polynomial methods. Alternatively, the loading to the system can be applied by moving the environment or vehicle system into the occupant model. This is implemented by assigning an acceleration function to certain bodies and segments representing either the floor or seat of the vehicle. In ATB, it is called the "Vehicle Motion." In MADYMO, the motion is applied to a joint connecting the body of the floor or seat to the reference space. The function can be defined as a list of coordinate pairs in both ATB and MADYMO with interpolation options.

MADYMO has an additional way of prescribing a detailed motion. It is done using a FE surface and applying a specific detailed motion to each node in the surface. This motion can be generated using a previously run FE simulation in MADYMO, LS-DYNA, or another model. The prescribed motion file contains time histories of the position or acceleration of each node. This method is useful for modeling local deformation of the floor in an UBB impacting only one foot of the occupant or for loading the occupant at an angle. Another loading option is to directly apply forces and torques to specific bodies and joints. In ATB, this is accomplished through the applied force/torque definitions and the joint actuator. In MADYMO, this is implemented through different types of actuators including body and joint actuators.

Both ATB and MADYMO include the capability of modeling airbags and use a dynamic gas flow model to inflate airbags. However, ATB uses an inflated ellipsoid to represent the airbag while MADYMO uses a FE shell airbag model. The FE model more accurately represents the shape of an inflating airbag and provides a higher spatial resolution for contact interactions with the occupant model. In our modeling experiments, the airbag capabilities were not exercised; however, they may be of interest in future endeavors.

In addition to defining all the initial conditions of the model, the user must also specify which outputs to generate during the simulation. In both ATB and MADYMO, the outputs that can be selected include acceleration, velocity, and position time histories of bodies and segments. Forces and moments are another output option in both models. MADYMO includes the additional option of using standard Society of Automotive Engineers (SAE) low-pass filters to post-process the output during the simulation (*5*). This type of signal processing would have to be performed in an external program when dealing with ATB output time-histories. One of the most important outputs to specify is the animation file. This file is crucial for comparing the kinematic accuracy of the simulation to experimental test results. Both ATB and MADYMO

produce output animations that are useful for analyzing the performance of a simulation. A more detailed comparison of the animation outputs is in the post-processing section of this report.

The ATB code restricts model size of rigid bodies and number of data points used in the vehicle motion. These restrictions are 100 rigid bodies total and 5000 points, respectively. On the other side of the spectrum, MADYMO's code has no restrictions on the size of the model. The user is only limited by the hardware platform being used. Restrictions on the size of the model create great limitations on the modeler. For example, a MADYMO user can create a model of a full vehicle and eight occupants, while an ATB user can only create a model with, at most, a couple occupants on basic seats.

4.   Modeling Methodology

The approach for modeling the test mannequin in the blast environment consisted of four main parts: (1) geometrical modeling of the vehicle, (2) positioning of the mannequin model in the vehicle, (3) applying the initial conditions to represent the blast loading, and (4) setting the contact models for the foot/floor and pelvis/seat interactions. For our initial exercise, we only modeled the internal floor and seat of the vehicle. These are typically modeled with planes, but more complicated seat geometries are modeled with ellipsoids. The ATD geometry was positioned on the seat to approximate the positioning of the ATD in the test setup. After the ATD was positioned, restraints were added such as 4- and 5-point seatbelt systems. We applied mostly acceleration time histories to the floor and seat structures for the blast loading; however, we also used velocity and position data. Different input types (acceleration, velocity, and position) were used depending on what experimental data were available and for the purpose of investigating their impact on model results. Generally, the model will not produce the same output response with inputs that are generated through numerical integration or differentiation. In fact, the model response may be drastically different depending on the input type. An in-depth investigation and explanation of this model response is outside the scope of this report. The parameters considered when modeling the internal vehicle geometry are the seat-back angle, seat-pan height off floor, and seat-pan depth (distance from edge of seat pan to seat back). These parameters are diagrammed in figure 2.
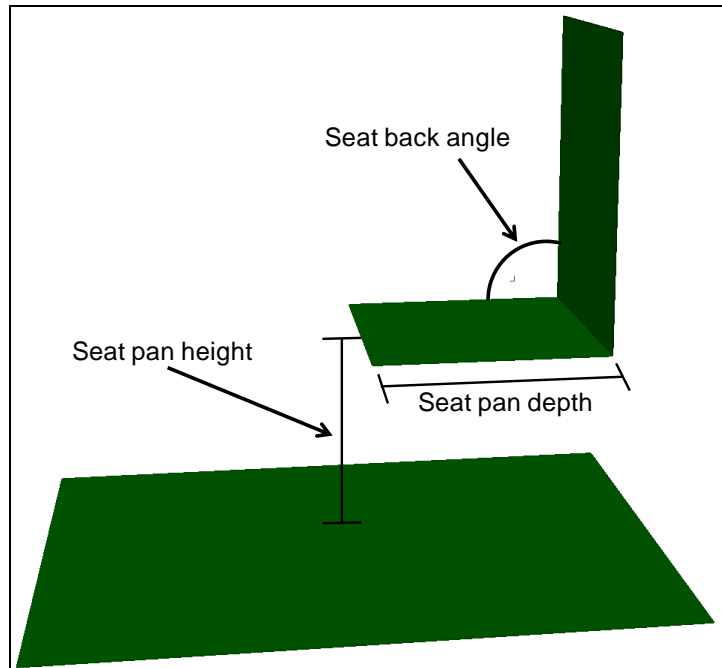
Figure 2. Internal vehicle geometry parameters.

The values of these internal vehicle geometry parameters are generally taken from measurements of the test setup or vehicle system. If the actual vehicle is not available, the parameters are estimated from pictures of the setup. The vehicle parameters can also be acquired by measuring dimensions of computer-aided design (CAD) geometry descriptions provided by vehicle vendors. In MADYMO, the CAD geometry can be meshed for an FE analysis. An accurate representation of the test environment is important for producing realistic ATD kinematics.

H3 ATD models are available in both ATB and MADYMO from a library of models provided by the software vendor. These models contain all the parameters that define their dynamic-response characteristics and generally do not need be modified. The H3 model requires correct positioning in the environment. Measurements taken from test setups such as knee angles, neck angles, and the distance of the feet from the seat are used to position the H3. As with the environmental setup, pictures of the test setup are also used for a visual comparison of the experimental positioning of the H3 versus the model positioning. After the H3 is placed in the correct seating position, seat-belt restraints are applied to the geometric model.

Various types of seat belts can be modeled in both ATB and MADYMO. The seat-belt design is up to the modeler and the possible configurations are virtually unlimited. Military vehicle systems typically use 4- and 5-point seat-belt systems rather than the 3-point seat-belt systems used in commercial vehicles. Seat-belt properties can be measured or taken from manufacturing specifications. Generally, the seat-belt parameters were taken from example files because many vehicle restraint fabrics have similar physical properties. Pictures are important for modeling accurate seat-belt positioning to produce realistic H3 kinematics. At this point, the model has the

initial positioning of the mannequin in the test environment including the restraint system. The loading to the system is the next component to be added.

The input accelerations are applied to the planes representing the floor and seat in both ATB and MADYMO. The planes move with the applied motion and load the H3 through the contact interaction models (described in the following paragraph). Separate motions can be input to the floor and the seat. (When replicating a test event, accelerometer data from the floor and the seat are used as the inputs in the models created with ATB and MADYMO.) The contact model is the transfer function that changes the floor motion into the forces loading the H3 models.

Contact models load the H3 at the foot/floor and pelvis/seat interfaces. The contact models in both ATB and MADYMO are modeled with force-deflection functions. This allows the plane representing the floor or seat to deflect or "penetrate" into the ellipsoids representing the surfaces of the H3. The force applied to the H3 is a function of this deflection and the rate of deflection. Both ATB and MADYMO are capable of modeling dampening and hysteresis for the contacts although they are implemented with different mathematical models. The contact function for ATB came from an example file provided with the software. The contact functions were empirically scaled to fit the test data. The contact function for the H3 interactions in MADYMO is built into the mannequin dataset. Contact functions can also be user created for both ATB and MADYMO. The functions can be derived from laboratory testing of the materials at the H3/environment interface. This is a useful feature and should be implemented when modeling experiments and test events that involve new materials with dynamic rate-dependent properties in the seat cushions and/or boots.

The last step we performed was setting the run controls and output signals. Then the model is ready to run. After the simulation is complete, the output traces may be compared to the experimental data for validation purposes or interpreted in their own right. The methodology for this post-processing analysis is described in section 5.

Other methodologies exist for modeling occupant response in vehicle systems exposed to the blast environment. One such method is developing an end-to-end model. This means that the blast threat is modeled in addition to the entire vehicle and occupant. This can be accomplished in one model suite or performed through coupling different models such as LS-DYNA and MADYMO. The current modeling methodology we use was described in this section; and these other modeling methodologies are described in section 8 of this report.

5. Pre-Processing

We define pre-processing to be the setup of the model input files to run the simulation. It includes defining geometries, masses, constraints, initial conditions, loading, interactions (contacts and restraints), desired outputs, and run control parameters such as time-step length and

start/stop times. The input files for both ATB and MADYMO are text files that can be created and edited in any text editor such as *Vim*, *Emacs*, or *Notepad*. The use of special pre-processing applications to edit input files is helpful for creating accurate models quickly. The pre-processors for both models provide GUIs for editing attributes of model components and provide visualization tools for previewing the input setup. Some model components are easier to edit through the use of the GUI while others are simple enough to edit via text editor. Overall, all the inputs in both MADYMO and ATB are structured ASCII text files. However, the structure of ATB input files is very different from the structure of MADYMO input files. The encoded feel of the ATB input file structure and the fact that MADYMO input files can easily be cut and pasted together, or even combined using include statements, makes creating, editing, and sharing models easier with MADYMO than with ATB.

5.1   Input Files

ATB input files (.lin files) are broken up into eight "cards," labeled cards A through H. Cards are broken down into subgroups such as card A.3 and card D.2.c. These cards are meant to organize the different parts of the input. For example, card B contains the physical characteristics of the segments and joints, while card C contains the description of the vehicle motion. The only descriptive words in the .lin file are the names of different segments, joints, and planes. Understanding the input file is not intuitive and requires the use of the ATB input description reference manual.

MADYMO input files (.xml files) are easier to understand when looking at the text file because they contain names for each element in the file instead of card numbers. The MADYMO input files are written in the XML. XML documents are designed to be machine-readable using standard software libraries, and are organized by hierarchy with parent and child elements in a similar structure to HTML. The element type is specified in bracketed tabs with its attributes as seen in the following example:

```
<BODY.RIGID
ID = "1"
NAME = "LowerLegLeft_bod"
MASS = "3.49"
INERTIA = "0.0474 0.0482 0.0064 0.0 0.0 0.0"/>
```

This makes the MADYMO XML format human readable and more intuitive, and eliminates the need for constant reference to the element dictionary in the reference manual. Valid MADYMO XML documents must adhere to the rules stated in the MADYMO document type definition (DTD). The DTD defines rules for the possible element types, which elements can be child and parent, as well as the required attributes and child elements of each element. Although a valid MADYMO XML input must follow the rules in the DTD, the user still has some freedom in structuring the input file. Additionally, the DTD specification allows other non-MADYMO software libraries, including user-written scripts, to open and manipulate MADYMO XML input without the need for any custom-written software. This drastically reduces the effort required to

produce an automated MADYMO input generator. By way of comparison, the bulk of an ATB automated file generation program is coded to simply parse the file.

ATB .lin input files must have the cards listed in the correct order for the input to be valid. However, MADYMO XML inputs can appear in different orders and elements can be grouped into SYSTEM.MODEL sections based on the user's choice. This freedom allows a user to create a MADYMO input that is readily understood. In ATB all the rigid bodies for the occupant, environment, seats, and other vehicle parts must be defined in the B card before all the contacts are defined in the F card. However in MADYMO, we can group all the elements relevant to the seat in one SYSTEM.MODEL including the definitions for rigid bodies, surfaces, and contacts. Then the elements relevant to the floor can be grouped in another system. This makes it easier for the user to find and edit the appropriate parts of the input file when needed. In addition, MADYMO input files allow users to include other external input files. This adds another level of organization to the input. The occupant is completely defined in a file that is separate from the file with vehicle definition. Combing multiple files using include statements makes the structure of MADYMO inputs modular, which increases order and makes it easier to create new or edit old models.

5.2   GUI

The MADYMO pre-processor, XMADgic, and the ATB pre-processor, ATB3I, both have GUIs that are useful for creating and editing input files. The programs have many similarities including a windowed interface with windows nested inside. Both programs assist in editing everything in the models from joint properties to loading conditions and time-step settings. However, the differences between the programs illustrate why we prefer XMADgic to ATB3I.

Both XMADgic and ATB3I have visualization windows for viewing the geometry of the current input file. In XMADgic, it is called the view geometry window, and in ATB3I, it is called the balancing window. This feature is useful because it allows the user to view the relative positions of the ATD and the vehicle while editing the file. The balancing window in ATB3I also provides the initial forces in the system so that the H3 can be placed in a stable state of equilibrium. These forces are not provided in XMADgic, so a short simulation must be run to calculate the initial forces in the system. Initial positioning of the ATD is vital for creating a good model. Both GUIs also contain help documentation to assist the user in editing the different components of the model.

The main difference between the pre-processors is that XMADgic edits the input file in a way that the user is more connected to the structure of the text file while ATB3I hides away the text input file from the user and edits model components in individual sub-windows. In XMADgic, the entire input file is shown in a specialized XML editor with each of the parent and child elements condensed in a concise form. To add elements such as another mass, ellipsoid, joint, etc., the user can browse an element dictionary and chose the desired element. Each of the attributes and child elements can then be entered by filling in the displayed fields. It is important

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for a model designer to understand the way the text input file is structured when working with groups of other modelers who may or may not use the GUI. The text file is the real input to the solver and errors/warnings may sometimes not be found in the GUI. The overall feel of the XMADgic pre-processor is a polished fluid interaction while using ATB3I feels clumsy and complicated. Some features in ATB3I are difficult to find, and editing parameters can be difficult and confusing.

XMADgic also clearly exceeds the capabilities of ATB3I for reusing input files or combining input files into one model. XMADgic allows the user to open multiple input files and easily copy elements from one file to another. XMADgic also enables the user to visually overlay multiple input files in the model viewer. To open multiple files with ATB3I, multiple instances of the ATB3I program must be run, and copy/paste options are very limited.

ATB3I runs using Microsoft's .NET framework and therefore will only work in the Windows OS. There are some problems using the ATB3I program in a corporate or Government setting where users do not have administrative rights to the computer. For some functions, ATB3I requires write access to Windows OS directories such as C:\Windows\Temp and C:\Windows\system32. These write permissions are usually not available to users without administrative privileges, and without write access, the ATB "balancing" window is non-functioning. The balancing window provides a key feature that makes using a GUI worthwhile to a modeler. Specifically, the balancing window allows the user to actuate the ATD model and see the actual changes with visualization. This feature also calculates and displays the initial forces on each part of the model so that the ATD can be positioned at a point of equilibrium. Without the balancing window, ATB3I is not very helpful. The rest of this pre-processing section assumes that the ATB3I program is running on a computer where all features are functional, unless stated otherwise.

5.3   Vehicle/Environment Modeling

We model the environment with simple geometry that roughly represents the vehicle system. This is done with planes and ellipsoids in both ATB and MADYMO. The vehicle can also be modeled as a FE facets connected to rigid bodies or a full FE model with solid, shell, and beam elements in MADYMO.

The basic vehicle modeling includes a plane for the floor and two planes at a right angle to model the seat. The seat does not need to be supported with planes because the motion of the seat is either fixed or locked to a prescribed acceleration trace. This basic seat is shown in figure 3.
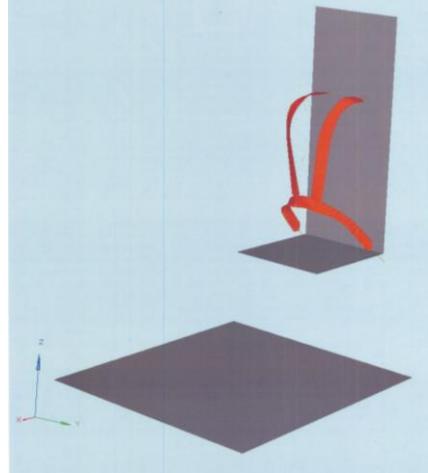
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Figure 3. Seat and floor constructed of planes in MADYMO.

In ATB, this is modeled by specifying the coordinates at three points in the plane. To change the geometry setup to match a different vehicle or test setup such as a different seat-pan height, each of the three points must be changed. In MADYMO, the plane is defined by three points and then attached to a rigid body. To move the plane after it has been defined, the user can simply change the free joint positioning between the rigid body and the reference space. Altering the seat geometry is a lot easier in MADYMO than ATB. For changing the seat-back angle, we can just change the angle position in the joint definition in MADYMO. However, in ATB, calculations have to be made by hand to determine the new coordinate positions of the corners of the plane defining the seat back.

Another advantage to using MADYMO for environment modeling is the capability to overlay CAD models in the geometry viewer. This is useful for modeling complicated CAD geometries with simple planes. Overlaying the planes with the CAD geometry is a quick way of setting up the dimensions of the plane to match the dimensions of the CAD. To create a FE model, an external FE pre-processor must be used to create the meshed geometry. We use LS-PrePost and Hypermesh to created FE meshes from CAD geometries. The format of the FE model for MADYMO is a listing of nodes and a listing of elements in an ASCII space-delaminated table. Our method involves saving the mesh as a LS-DYNA keyword file (.k) and then copying the text from the keyword file and pasting it into XMADgic in the proper table. A picture of a FE vehicle geometry modeled in MADYMO is shown in figure 4.
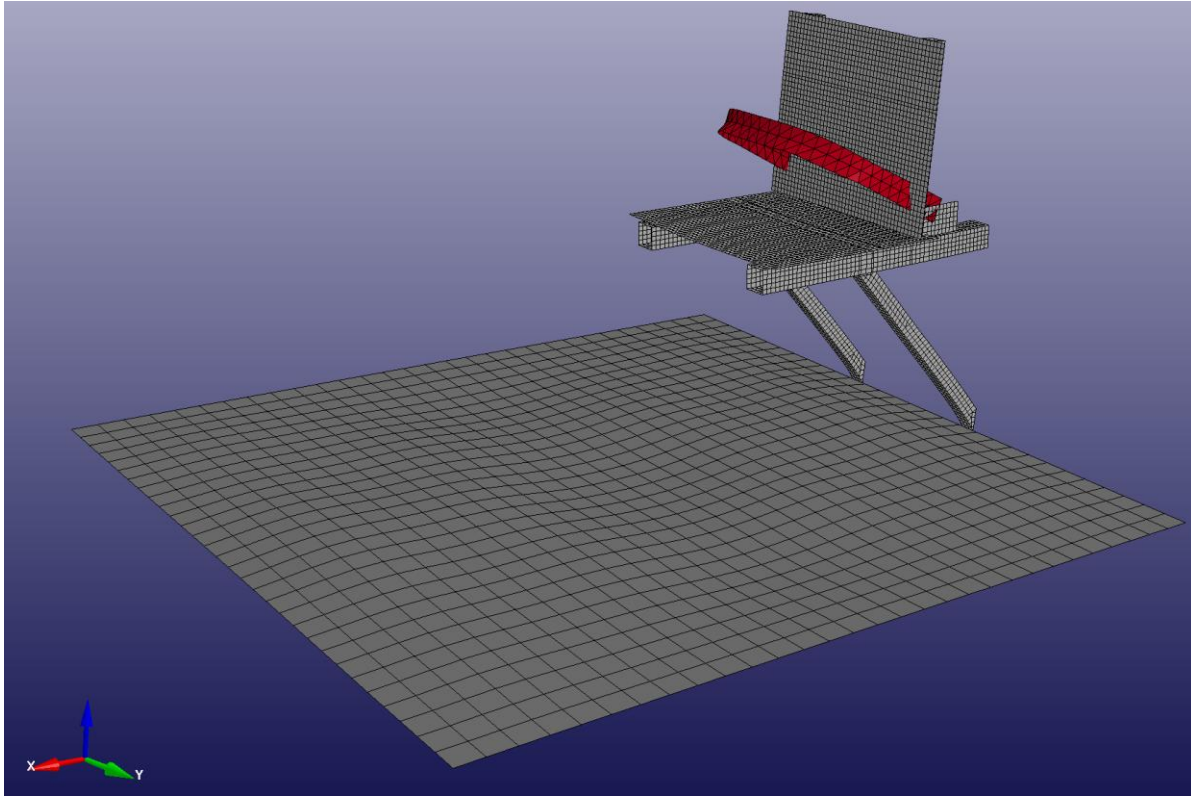
Figure 4. FE floor and seat in MADYMO.

FE models of the floor and seat add more spatial resolution to localized movement. It allows the floor to bend and oscillate with vibration nodes and anti-nodes, which may make safer foot positioning more apparent.

5.4 ATDs

The ATD models are produced from validated data sets in both ATB and MADYMO. ATB uses the GEBOD program to insert a dataset representing the 50th percentile H3 ATD in the ATB input file. GEBOD's H3dataset was developed from measurements made by the Armstrong Aerospace Medical Research Laboratory (AAMRL). MADYMO uses H3 datasets from TASS measurements. Both the ATB and MADYMO occupant databases also include human models and different variations of the H3 mannequin. In fact, TASS continues to release new occupant models each year for different types of crash-test mannequins and ATDs.

ATB has two 50th percentile H3 models: one basic model and one model with a more detailed lower extremity constructed out of more ellipsoids. For our models, we used the more detailed model. These models are shown in figure 5.
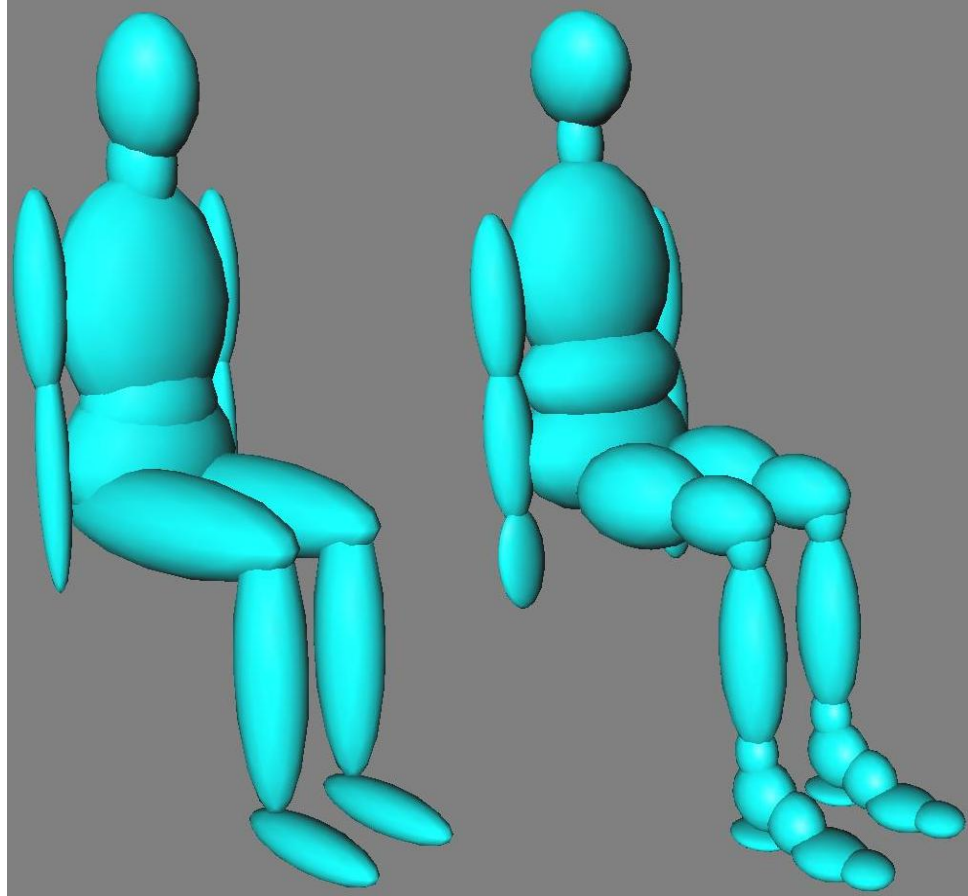
Figure 5. ATB H3 50th percentile (left) and H3 50th percentile with detailed lower extremity (right) models.

MADYMO has many iterations of the 50th percentile H3 model as they continue to update their releases: a basic H3 ellipsoid model, a Q (quality) H3 ellipsoid model, and the Q facet model (with FE facets). The Q models are shown in figure 6.
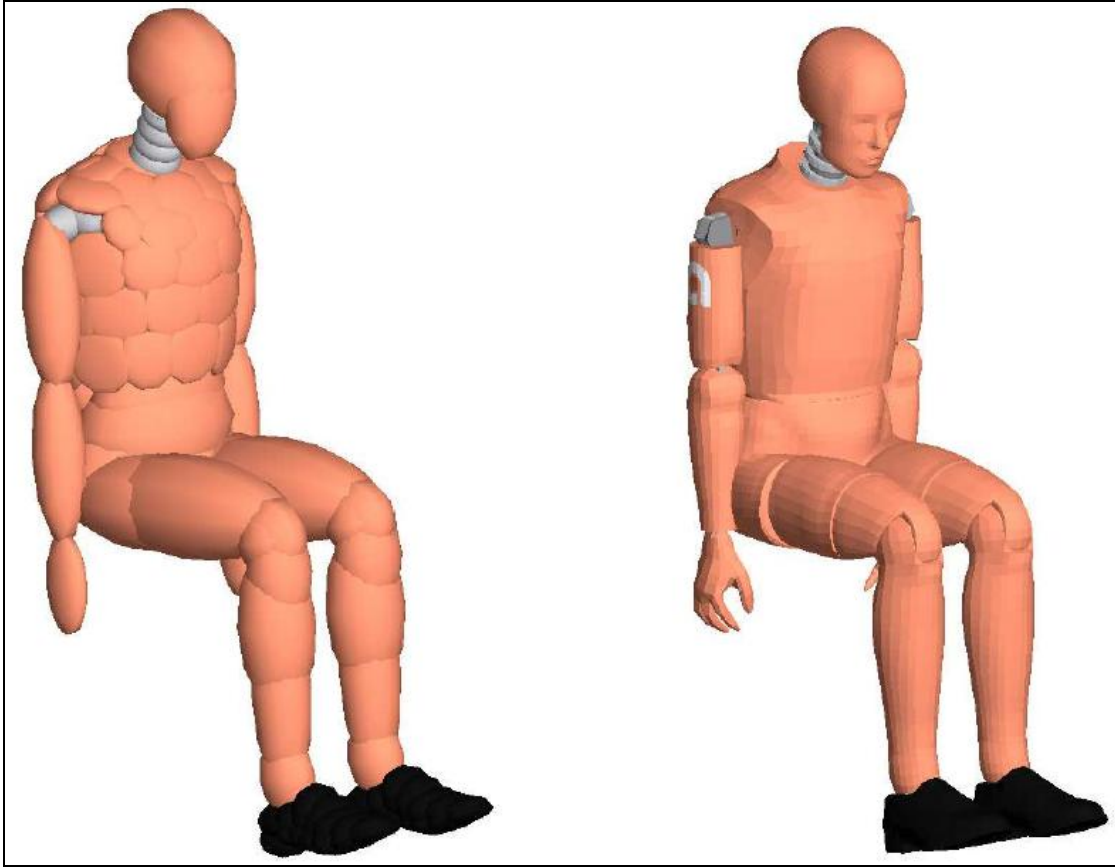
Figure 6. MADYMO Hybrid III 50th percentile ellipsoid Q (left) and facet Q (right) models (*3*).

We primarily used the H3 ellipsoid Q model, although we will be conducting and reporting on a detailed comparison between the available MADYMO H3 models in future research efforts. The ATB H3 with detailed lower-leg model is constructed of 33 ellipsoids and the MADYMO Q H3 ellipsoid model is constructed of 242 ellipsoids. This increase in spatial resolution makes the MADYMO model more desirable.

The models of the ATDs have all the parameters set and even include contact functions. The ATD model is one of the most important components to the overall system model. It is very useful that these models are provided by the software vendor and that they are already verified under certain impact conditions. However, the loading conditions to which we subject the model for UBB applications are of higher magnitude and shorter duration than the loading conditions for which the models were validated. Developing these ATD models from scratch is beyond the scope of most of our projects due to resource constraints. We are now working with the vendor, TASS, to improve the Q model for the UBB use-case. Currently, our modeling process is simply choosing an occupant model and inserting it into the input file with the vehicle environment.

Positioning of the ATD is simplified with the use of the GUIs in both ATB and MADYMO. The user can simply position the ATD to be as close as possible to the seat or with a slight deflection

into the seat. The balancing window in ATB displays the initial forces on the system so that the ATD can be placed in a state of rest or equilibrium. In MADYMO, one may start the simulation at a negative time to allow gravity to pull the dummy into the seat cushion to reach equilibrium before the loading conditions are applied. This is called pre-simulation. It is possible to perform a pre-simulation in ATB. However, one cannot run the simulation at negative time values; every ATB simulation must start at time 0. In addition to positioning the model ATD at the correct distance from the seat, the limbs of the model must be articulated to match the test event. This is usually done by rotating limb joints and visually comparing the ATD setup in the model to a picture of the test setup. If specific measurements were taken of the test setup, the angles can be used in the input file.

Overall, with the modern and easy-to-use interface, we prefer using MADYMO over ATB when positioning an ATD in a model.

5.5   Seat Belts and Harnesses

After the ATD is in the correct position, the seat belt can be created and tightened to fit. ATB can only model simple belts, and it not trivial to add belts or modify belt configurations using the ATB3I program. It is much easier to model simple belts in MADYMO. Also, it is easier to create a new FE belt around a H3 ATD in a MADYMO model than to create a simple belt around a H3 in ATB.

Adding the basic seat belt in ATB can be quite difficult and time consuming, because each of the coordinates where the belt contacts the ellipsoid on the ATD model must be entered manually. There is no tool in the GUI that assists the user in calculating the coordinates on the surface of the ellipsoid, so determining the values needs to be done by hand or in an external program.

The MADYMO pre-processor, XMADgic, has a feature called the "belt fitting wizard," which assists the user in adding or modifying seat belts in the model. With the belt fitting wizard, we select start and end points for the belt and the type of FE belt. Then, the wizard creates and tightens the belt automatically. Although this automation occurs, there are user-defined parameters that can be set to adjust the belt and fitting. Sometimes, the belt fitting wizard fails to find a fit for the belt and cannot correctly wrap the belt around the occupant. With continuing support from the vendor, we hope there will be improvements made to the belt fitting wizard. Overall, the belt fitting wizard in MADYMO makes the belt modeling process efficient and relatively painless. This is another reason we prefer to use MADYMO over ATB.

5.6   PPE

PPE such as helmets and ballistic vests/plates can be added to the ATD model description to match the test setup where PPE is often used. It is important to add the PPE to the model, because the equipment an ATD wears affects the volume, mass, moments of inertia, and contacts of the system. The FE capabilities of MADYMO make it possible to create PPE models with more accurate behavior. This includes modeling deformable vests and flat armor plates to create

better contacts with the environment. Since the coupling of the mass of the PPE to the ATD is one of the most important impacts that we aim to analyze with these models, using MADYMO FE PPE models will be more useful than simple rigid ATB PPE models.

5.7   Prescribed Motion

We often like to create a model and then change the inputs or prescribed motion to the floor and or seat to analyze the response of the system to a set of different loading conditions. Changing the inputs requires pre-processing the ATB and MADYMO input files.

Setting the motion of the floor and seat in ATB can sometime be difficult due to the specific requirements imposed on the input file. The "vehicle motion," as it is called in ATB, is set by a table of accelerations, velocities, or positions. Three linear and three rotational values must be defined for each time value. The time increment must be a constant and each line is ended with the word, "CARD C.5". Acceleration traces recorded during experiments generally only have two columns, one for the time and one for the magnitude of acceleration, even if they are multi-axis accelerometers. There is usually one file for each axis. Each of the traces would need to be combined into one table to be used in ATB. The table can be copied into the GUI, or the card number can be added to the end of each line and then pasted into the ASCII input file. If only one axis of movement is being prescribed to the floor and/or seat, zeros must be filled in to complete the table. This is a process that takes time to do by hand, so it was automated by creating simple text manipulation scripts using Bash, AWK, and Python.

On the other hand, defining prescribed motions for MADYMO input files is quite easy and straightforward in both text editors and the XMADgic GUI. Each time a function needs to be assigned to any feature or component of a model in MADYMO, it can be defined anywhere and can start at any abscissa value. Also, the increments between points in the function do not need to be uniform. This adds flexibility to the user input. The functions can be cut and pasted from an accelerometer data file with no extra pre-processing necessary. The flexibility in the MADYMO input file scheme makes it much easier to either manually change the input loading or to script the input loading with automation. This is yet another reason we prefer to use MADYMO over ATB.

6.   Simulation

After the model input is completed the solver is used to simulate (or run) the model. Both the ATB solver and the MADYMO solver can be run from the command line or the pre-processor GUIs provided with the software. Run times for models with rigid bodies only with similar complexity are roughly equal for ATB and MADYMO. The run time is a function of the time-step and the total simulation time. Using more computationally expensive model features in MADYMO, such as FE components and gas-flow in airbags, can cause the run time to increase

drastically. In MADYMO the time-step can be automatically calculated when there are FE models. The size of the FEs determines the time-step: smaller FEs create smaller time-steps and smaller time-steps make the total run time longer. To reduce run-time in MADYMO, multiple processors may be used. This can be implemented by using a multi-core workstation or running MADYMO on a supercomputer cluster. However, this only reduces run time when large amounts of FEs are present in the model. If the model is only comprised of rigid bodies, it should have a relatively quick run time and minimal performance enhancement will be gained by using multiple processors. This is why it is not important that ATB does not have multiple processing capabilities.

After the run completes, a file is created in both ATB and MADYMO with a list of warnings and errors. Errors cause the simulation to fail and stop. Warnings are messages produced by the solver of possible problems with the simulation, but they are not fatal errors and the simulation can still be completed. Sometimes warnings are important and other times they may be ignored. For example, warnings about the extrapolation of functions used in joint properties or contact definitions are important and should be taken into consideration for the validity of the simulation. However, warnings about a user-defined function not being used or assigned to a model element may be purposeful and just an extra part of the input file to be used in other simulations.

For the most part, warnings and errors should be useful and help in making improvements to the model. As with debugging in programming, warnings and errors may be difficult to interpret. Both ATB and MADYMO produce files with errors and warnings. ATB's warnings and errors are more coded and difficult to understand than the errors and warnings produced by MADYMO. With a difficult set of error and warning messages, it is more challenging to debug ATB input files than MADYMO input files.

There a couple different types of scenarios where ATB and MADYMO may produce warnings and/or errors. The simulation may or may not crash as well. If an input file is not valid in MADYMO, specific error messages will be produced and the simulation will not run. This is not considered a run-time error. In ATB, however, if an invalid input file is run, a Fortran run-time error is produced with no indication as to the source of the error. This makes it difficult to determine the problem and fix the input file. No errors or warnings are logged in any files. An example of the error message is shown in figure 7.
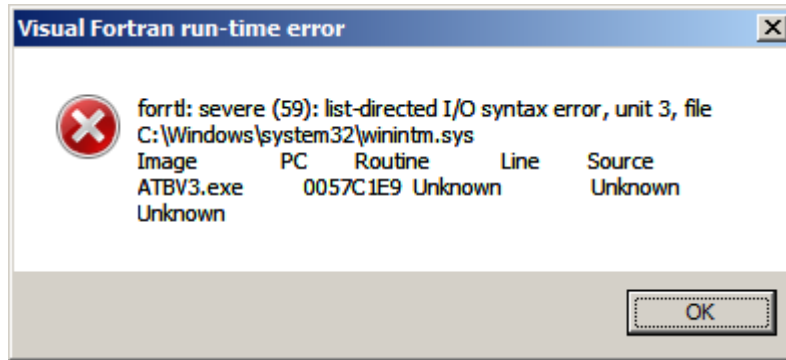
Figure 7. ATB Fortran run-time error message window.

Both ATB and MADYMO produce the animation files while the simulation is running. If there is a problem with the simulation and the run crashes or stops before completing, the animation file can still be viewed. This partial animation file can be used with the error and warning logs produced by the programs to determine what went wrong in the simulation. The animation can be viewed up until the point the program crashed. This is a useful feature in both ATB and MADYMO. After figuring out what went wrong with the simulation, the input file can be fixed and the simulation can be run to completion.

Overall, both ATB and MADYMO can create fast running rigid-body models. When larger, more complicated models are created in MADYMO, the run time will increase. However, the flexibility MADYMO provides by allowing more complicated components to be added for increased spatial and/or temporal resolution in simulation results can be worth the increase in run time depending on the model use-case. This is an advantage for using MADYMO over ATB. Also, MADYMO error messages and warnings from run-time errors are more useful overall and are easier to debug than ATB error messages and warnings.

After the simulations are run in either ATB or MADYMO, the output files are usually post-processed for analysis.

7. Post-Processing

Post-processing of simulation results involves manipulating the results data, viewing animation files, comparing the results to experimental data, and presenting the results. The post-processing tools available include specialized post-processors for ATB and MADYMO models, custom-built software tools, and multi-purpose post-processors such as those included in the Altair Hyperworks suite. This section describes the output files produced by ATB and MADYMO models, attributes of the output signals, post-processing software, and comparison methodologies.

7.1 Output Files

Output files from the models come in two main types: ASCII text and binary data. ASCII text files contain the data as numbers and text, and can be opened in text editors. Binary data are more efficient for compression and save disk space, but can only be opened with the correct program. However, binary data files can be used by custom programs to input and output data faster than writing to text files. The data contained in the output files include log files of the simulation with errors and warnings, data traces of accelerations, positions, velocities, forces, moments, etc., and animations.

Both log files from ATB and MADYMO simulations are ASCII text data. Simple post-processing scripts were written and used to parse relevant data for inputting into a database. Data traces from ATB simulations are output in ASCII files with the extension .t21, .t22, .t23, etc. The number of .t2* files created depends on how many traces are set as outputs in the model. The order of the traces in the .t2* files depends on the order specified in the model as well. Multiple traces are contained in each .t2* file, and trace names and types are located as text at the top of the file. Since the filename does not specify which outputs are contained within it, it can sometimes be time consuming to find specific traces. As long as the output settings in the input file have not been changed, the traces will remain in the same file. Another difficulty with the ATB output data trace files is that headers for each page are in the file if the file was to be printed. These need to be removed for the data trace to be used in graphing and other post-processing activities. We programmed a set of scripts using AWK and Python to extract the data traces from the .t2* files into our own set of data files. Each of the data trace files we created contains only time and signal values, and the description of the data trace including signal type and units is in the filename. This greatly simplified the use of the data signals in the other post-processing activities.

Time history data traces from MADYMO simulations can be output in four different formats: MADYMO's default file format (MAD), comma separated value (CSV), Hierarchical Data Format 5 (HDF5), and Altair Binary Format (ABF). Both the MAD and CSV format are text files that contain the data. The HDF5 and ABF formats are binary data files. Also, recently, a new option has been added to output the MADYMO data traces in the International Organization for Standardization (ISO) technical specification (TS) 13499 multimedia data exchange format. We have created a script here to convert data traces from the ISO/TS 13499 format to the standard Aberdeen Test Center (ATC) ASCII file format. The ATC ASCII file format comes from extracting all the traces from a test event, which are stored in a HDF5 file. These traces are extracted using ATC's "Analyzer" software program. The ASCII file format that comes out is the file type that our analysts are most familiar with and a format that is compatible with our analysis software. Having output from our simulations match the output format from live-fire tests greatly facilitates comparing the results. So, our current methodology is to have MADYMO output the data files using the ISO/TS 13499 format and then run our script, which converts the ISO format to the ATC format.

The .t2* files from ATB are drastically more difficult to work with and are less user friendly than the ISO/TS 13499 files from MADYMO. There is no simple way to script the conversion of the .t2* files from ATB. This is why we prefer the MADYMO output data file options over ATB.

7.2   Output Signals

Post-processing of the raw data from simulations often involves filtering and/or resampling the data traces. ATB has no filtering capabilities built-in, so we use a Python script to filter the data with low-pass Butterworth filters. The SAE has prescribed specific filters to be used on time-histories from ATDs in the SAE J211 report (*5*). These filters are called Channel Frequency Class (CFC) filters. MADYMO automatically filters each ATD channel with the appropriate CFC filter. This can be useful or unnecessary depending on the post-processing analysis we want to perform. Fortunately, the filtering in MADYMO can be disabled.

7.3   Animation Files

One of the most important outputs of simulations performed in ATB and MADYMO are the animations. Viewing animations can reveal problems and successes in models very quickly. An accurate representation of the kinematic response of the ATD is one of the main goals in producing a proper model. These animation files are often compared to videos of real ATDs in test events.

The animation files produced in ATB simulations are ASCII files with a .sa1 extension. These files can only be viewed using the ATB3I program. MADYMO animation files can be output in three different formats: MAD, HDF5, or D3PLOT. The MAD format is the default MADYMO format and is an ASCII file. Other animation data are placed in FEMANI and CNTANI files. These files contain FE contour data and contact contour data, respectively. MAD animation files can be viewed using the MADPost software or third-party post-processors such as Altair's Hyperview program. HDF5 and D3PLOT are binary files. The D3PLOT is a LS-DYNA file type. D3PLOT animations can be viewed using MADPost, LS-PrePost, or Hyperview. Using a D3PLOT animation file type makes comparing MADYMO simulations to LS-DYNA simulations quite easy.

Being able to easily share the output animation files from MADYMO with members of the LS-DYNA community, as opposed to ATB animation files which cannot, is why we prefer the MADYMO output animation file format options.

7.4   Comparing Simulations to Experimental Data

We compare both animations and time-histories from simulations to the videos and time-histories from experiments. Most of our time-history comparison techniques are custom coded in external programs rather than using the post-processing software provided by the model vendors. However, for comparing animations with videos, we use both MADPost and Hyperview.

The simplest way to compare time history data is by graphing both traces on the same plot. This can be done in any graphing program. We prefer programs such as DPlot and gnuplot. Plots of the time-histories can also be created in MADPost and Hyperview. To quantify how much two time-histories match, we use many different metrics.

We compare peak values, timing agreement, and shape agreement. We have coded scripts to perform these comparisons automatically on our time-history data traces. We compare shape agreement by calculating the normalized cross-correlation between two traces. Similar comparison can also be performed in one of the included MADYMO post-processors called Objective Rating. This software allows us to compare many different traces and create a matrix of peak comparisons, timing comparisons, and other comparisons such as the WIFac metric, which is a measure of shape agreement computed using integrals.

To compare animations with videos from experiments, they are often played at the same time. Post-processors such as MADPost and Hyperview allow an analyst to import MADYMO animations and videos of test events. These can then be viewed side by side and set up to play together. If we would like to use an ATB animation in this way, we have to first convert the ATB animation to a video file using external screen capture software and then import the video file. This means that one would not be able to rotate or change the view of the animation in the post-processor.

The fact that ATB output animations are not compatible with our post-processing software is another reason why we prefer MADYMO over ATB. Also, the MADYMO software suite includes a very useful post-processor, MADpost, for comparing the animations to video of the test event.

8.   Model Coupling

The current predominant use-case of ATB or MADYMO under consideration is modeling an occupant response for a vehicle exposed to an accelerative threat. In this use-case, the ballistic threat and vehicle loading is mostly simulated in an external model. Therefore, it is necessary to consider how an accelerative-threat model may be coupled to either MADYMO or ATB, and the effects of that coupling on the accuracy and run times of the model. As explained previously, the most frequently used method of transferring the vehicle loading into ATB and/or MADYMO is by running an external model and averaging the vehicle response to an overall velocity profile for the entire floor or seat surface. This velocity-time history is then applied to the geometry that will load the occupant.

The difficulty in this lies in understanding what is "global motion" versus "local motion," also known as "local dynamic deformation." The response output from a full system-level simulation of a live-fire test in LS-DYNA with loading model, vehicle, and occupants will be a combination

of global motion and local motion when the velocity profile of a group of nodes of the floor and seat are averaged and output. Using these averaged velocity profiles to move the floor and seat geometry requires intermediate coding "glue" to process output text files from FE models and put the text representing the motions into ATB and MADYO input files. These methods are the simplest; however, some simulations exhibit unexpected behavior, perhaps due to sampling rates, of the floor velocity profiles, and warrants further investigation. This method of one-way coupling is very rudimentary and not automated through supported channels such as software developers.

ATB has limited capability of interacting with an external FE model. It can model one deformable FE body, which must be simulated for vibration modes and response externally. The FE model and ATB are not coupled in a step-by-step manner, but instead the resulting analysis from the FE model is included in the motions of the ATB rigid-body model. This coupling method is no longer supported by developers of ATB and was not thoroughly investigated, as implementing it would be a difficult task with the unsupported code and features.

MADYMO, on the other hand, has a direct coupler that can be used with well-known FE models such as LS-DYNA. This coupler allows MADYMO and LS-DYNA to talk back and forth for each time step, which is known as full two-way coupling. LS-DYNA will calculate forces, pressures, etc., of the vehicle structure and impart them on the MADYMO occupant models. The occupant models' positions and force vectors then change and are loaded back on the LS-DYNA vehicle structure. This continues until the simulation completes. This method has some disadvantages as it has a very long run time, longer than the run time of separately running MADYMO and LS-DYNA simulations combined.

A quicker running alternative is available in MADYMO. This method is called prescribed structural motion (PSM) and is a version of one-way coupling. In the PSM methodology, a structural component, such as a seat or floor, will be modeled as a FE mesh in LS-DYNA or another external FE model (FEM). The LS-DYNA FEM is then simulated with loading applied to the structure and the response of the structure is captured. The structural response is output from the FEM as a PSM file. The PSM file contains a set of node-position time-histories. Back in the MADYMO model, there is an identical FE structure that represents the floor and/or seat. The motion of this surface, which is captured in the PSM file, is then applied to the structure in MADYMO. The floor and seat structures will move in MADYMO the same way that they moved in the LS-DYNA simulation. This motion is a response motion in LS-DYNA and it is a forced loading motion in MADYMO. The floor and seat structure will move in MADYMO the same way that they moved in LS-DYNA. In MADYMO, PSM interacts and loads the occupant in a one-way path. The floor and seat act on the occupant and apply a force to it, which moves the occupant. However the occupant's force on the floor and seat will not move those structures. The floor and seat only move with the prescribed motion as determined from LS-DYNA and depicted in the PSM file's node-position time histories. This PSM methodology has a shorter run time than a direct coupling methodology. Also, one LS-DYNA simulation can be run to generate

a PSM file, which is the most time-consuming step, and then multiple MADYMO simulations can be run using the same PSM file. This is useful for analyses such as determining the safest occupant positioning in a seat giving the same loading and floor and seat response/motions. The assumption in using this PSM methodology is that the occupant model does not have a significant impact on the structural response of the vehicle floor and seat. This is because there is no feedback for the seat and floor motion from the position or motion of the occupant. This is a fair assumption in the case of the floor; however, it may not be a good assumption in the case of the energy absorbing type seats, etc. The modeler should use good judgment on which cases and when to use PSM.

The additional options for coupling models in MADYMO provide flexibility in our methodology when moving forward with the UBM program. This is an advantage over the lack of features in ATB.

9. Accuracy of Simulations

Both ATB and MADYMO are capable of producing accurate simulations. Accuracy of the simulation may be judged on the kinematic response of the occupant and/or the simulated forces and moments of the occupant. A general idea of the accuracy of the kinematic response can be judged by overlaying videos of tests with animations created from the simulations. This can also be done with traces of forces and/or moments. We have also used more quantitative techniques for comparing the force, moment, and acceleration traces of the occupants. Some metrics we have used include signal peak agreement, presence of phase shifts, and shape agreement metrics, such as dynamic time warping (DTW) and normalized cross-correlation.

We observed that models we created using out-of-the-box ATD configurations in MADYMO performed more accurately using the aforementioned metrics than the out-of-box performance of ATB models. However, the exact advantage in terms of results correctness is not clear, especially for lower tibia. ATB has been shown to be response-bounding for tibia axial compression (*6*). MADYMO has not been observed to perform similarly for the tibia. For spine prediction, the advantage of MADYMO may be simple. The MADYMO advantage for spine prediction may be attributed to the superior level of software model support; the H3 model in MADYMO is much more detailed than the H3 model in ATB, including for the abdominal and thoracic region. The MADYMO H3 contacts have been the subject of extensive verification and validation effort. Though they have been developed for slower automotive-loading rates, they still appear to be superior to the ATB contact functions.

Nevertheless, the observed performance in our simulations is not an end-all indicator for improved accuracy of simulations in MADYMO models over ATB models. The accuracy of the simulations depends highly on the expertise of the modeler and the assumptions of the model.

We believe that equally accurate models can be created in both ATB and MADYMO. A high-fidelity H3 model can be created from scratch by the modeler in ATB with even more spatial resolution than the MADYMO H3 Q model. This would, however, take extensive effort on the part of the modeler. The assumptions made when coupling structural movement to the loading of the occupant also drive the accuracy of the simulation. Depending on the methodology chosen, steps may be needed to increase the accuracy, including filtering, contact function editing, etc. Coupling options available in MADYMO make it more useful than ATB to determine which methodology produces the best results for the model applications. The features in the MADYMO software suite make producing accurate models simple and quick. The use of FE components in MADYMO allows the modeler to create simulations with high spatial accuracy. However, it still depends on the expertise and skill of the modeler to create accurate simulations. The accuracy of the simulation is also dependent on how much test data and specifics about the test set up are available to the user. Without proper input parameters, the model will not produce accurate results.

Overall, both ATB and MADYMO can produce accurate simulations However, MADYMO provides features and tools that make it easier and quicker to develop models that produce accurate simulation results. By facilitating the user, MADYMO provides a workspace environment to create accurate models. ATB does not provide the tools to easily create accurate models.

10. Conclusion

Although ATB and MADYMO share a similar modeling methodology, they each have distinct advantages and disadvantages, as noted in this report. Careful consideration suggests preferences for use of each and recommendations for a path forward for use of rigid-body computational models for simulation of UBB effects on vehicle occupants. The chief categories for comparison of the two models are licensing costs, ease of use and productivity, and correctness of results. Though ATB is attractive from a cost perspective, MADYMO offers superior ease of use and productivity, and has advantages in correctness and reliability of results. ATB's cost advantages are also outweighed by the fact that ATB would require in-house software maintenance. Based on these advantages over ATB, we recommend that MADYMO be preferred over ATB for use as a multi-body modeling tool.

Also, we argue that the high license costs of MADYMO are rapidly recouped in terms of productivity. The pre- and post-processing tools included with MADYMO render modeling substantially easier, and, therefore faster, than modeling with ATB. If a new model must be constructed from scratch, we estimate that a model may be prepared in MADYMO in half the time required using ATB. Ease of analysis of results is similarly biased towards MADYMO; notably, ATB does not even have signal visualization tools. All extraction and analysis of output

signals from ATB requires custom-written scripts, which constitute a significant investment of labor. The lack of support and tools for ATB render its use much more labor intensive than MADYMO. If analyses are standardized, then these labor costs may no longer be dominant; however, while modeling is still developmental, they should be considered substantial.

We have observed in limited cases that MADYMO can produce more accurate results than ATB. However, the advantage in terms of results correctness for out-of-the-box models is not why we prefer MADYMO to ATB. Modeling using MADYMO is a better choice for producing accurate results because of the tool set it provides to the user. MADYMO features and tools provide the user with a better work environment to create models that produce accurate results.

The advantages of using MADYMO over ATB are abundant. MADYMO has a large user base, even in the defense industries. Within Government, TARDEC and NAVAIR are using MADYMO for rapid prototyping of blast-threat analyses; and we found collaboration with the latter especially valuable. In fact, NAVAIR is actively developing end-to-end solutions for UBB modeling in MADYMO. Use of a standard platform allows code-sharing, improved problem solving, and possible license sharing. MADYMO is a reasonable choice as a primary multi-body and FE toolset for the UBM program.

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List of Symbols, Abbreviations, and Acronyms

ABF   Altair Binary Format

AFRL   Air Force Research Laboratory

AAMRL   Armstrong Aerospace Medical Research Laboratory

ARL   U.S. Army Research Laboratory

ATB   articulated total body

ATC   Aberdeen Test Center

ATD   anthropomorphic test device

CAD   computer-aided design

CFC   Channel Frequency Class

CSIR   Council for Scientific and Industrial Research

CVS   Crash Victim Simulation

CVS   comma separated value

DTD   document type definition

DTW   dynamic time warping

FE   finite-element

FEM   FE model

FFI   Norwegian Defense Research Establishment

GDLS   General Dynamics Land Systems

GUI   graphical user interface

H3   Hybrid-III

HDF5   Hierarchical Data Format 5

ISO   International Organization for Standardization

LFT&E   live-fire test and evaluation

MAD   MADYMO default file format

MADYMO   mathematical dynamics model

MB   multi-body

MPI   message passing interface

MPP   massively parallel processing

NAVAIR   U.S. Navy Naval Air Systems Command

OS   operating system

PPE   personnel protective equipment

PSM   prescribed structural motion

SAE   Society of Automotive Engineers

SLAD   Survivability/Lethality Analysis Directorate

SMP   symmetric multiprocessing

TARDEC   U.S. Army Tank Automotive Research, Development and Engineering Center

TASS   TNO Automotive Safety Solutions

TS   technical specification

UBB   under-body blast

XML   extensible markup language

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